

We have now covered the basic X-ray emitting atomic processes as well as **collisional plasmas**. Now we will cover:

- Synchrotron Radiation
- Compton/Inverse Compton Radiation
- Absorption *and*
- **Photoionized Plasmas**  
(where  $k_B T_e \ll$  Ionization energy of plasma ions)

## Emission III: Photoionized Plasmas (and continuum processes)

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### Introduction

We will again make some initial assumptions about our “astrophysical plasmas”:

- They are dominated by H and He, with trace metals.
- Nuclear transitions are insignificant.

**However, now magnetic fields will play an important role, and it will not always be true that electrons have a Maxwellian velocity distribution!**

### Cyclotron/Synchrotron Radiation

Radiation emitted by charge moving in a magnetic field.

First discussed by Schott (1912). Revived after 1945 in connection with problems on radiation from electron accelerators.

Very important in astrophysics: Galactic radio emission (radiation from the halo and the disk), radio emission from the shell of supernova remnants, X-ray synchrotron from PWN in SNRs...

## Cyclotron/Synchrotron Radiation

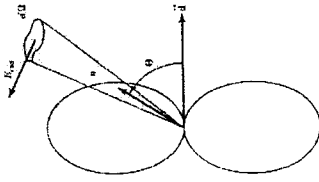
Cyclotron radiation comes from a non-relativistic electron, gyrating in a magnetic field, while synchrotron radiation is by definition relativistic.

(As with Bremsstrahlung, a rigorous derivation is quite tricky.)

In the non-relativistic case, the frequency of gyration in the magnetic field is

$$\begin{aligned}\omega_L &= eB/m_e c \\ &= 2.8 B_{1G} \text{ MHz (Larmor)}\end{aligned}$$

And the frequency of the emitted radiation is  $\omega_L$



## Synchrotron Radiation

The total emitted power is:

$$P = \frac{2e^4 B^2}{3m_e^2 c^3 \beta^2 \gamma^2} = \frac{2}{3} r_0^2 c \gamma^2 B_{\perp}^2 \quad \text{when } \gamma \gg 1$$

Or, alternatively  $P \propto \gamma^2 c \sigma_T U_B \sin^2 \theta$  (where  $U_B$  is the magnetic energy density)

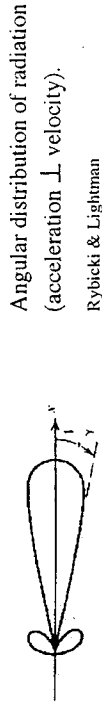
$$\text{and so } P \sim 1.6 \times 10^{-15} \gamma^2 B^2 \sin^2 \theta \text{ erg/s}$$

Electron lifetime:  $\tau \propto E/P \sim 20/(\gamma B^2) \text{ yr}$

This is sometimes called "electron burn-off"; in the Crab Nebula, the lifetime of an X-ray producing electron is only 20 years (!)

Note that  $P \propto 1/m^2$ : synchrotron is negligible for massive particles.

## Synchrotron Radiation



Angular distribution of radiation  
(acceleration  $\perp$  velocity).  
Rybicki & Lightman

Synchrotron radiation comes from relativistic electrons interacting with a magnetic field. In this case, the emitted radiation is "beamed" along the velocity vector, with an opening angle

$$\Delta\theta \sim 1/\gamma$$

Gyration frequency  $\omega_B = \omega_L/\gamma$

Observer sees radiation for duration  $\Delta t \ll T = 2\pi/\omega_B$

This means that the spectrum includes higher harmonics of  $\omega_B$ . The maximum is at a characteristic frequency which is:

$$\omega_c \sim 1/\Delta t \sim \gamma^2 e B_{\perp} / mc$$

## Synchrotron Radiation

Synchrotron radiation comes from relativistic electrons spiraling around magnetic fields. Can we use X-ray measurements to determine either the:

- electron distribution?
- magnetic field?

## Synchrotron Radiation

Assume the energy spectrum of the electrons between energy  $E_1$  and  $E_2$  can be approximated by a power-law:

$$N(E) = K E^{-\rho} dE \quad (\text{isotropic, homogeneous}).$$

where  $N(E)$  is the number of  $e^-$  per unit volume

Intensity of radiation in a homogeneous magnetic field:

$$I(\nu, k) = \frac{\sqrt{3}}{\rho + 1} \Gamma\left(\frac{3\rho - 1}{12}\right) \Gamma\left(\frac{3\rho + 19}{12}\right) \frac{e^3}{mc^2} \left(\frac{3e}{2\pi m_e c^5}\right)^{(\rho-1)/2} K[B \sin \theta]^{(\rho+1)/2} \nu^{-(\rho-1)/2}$$

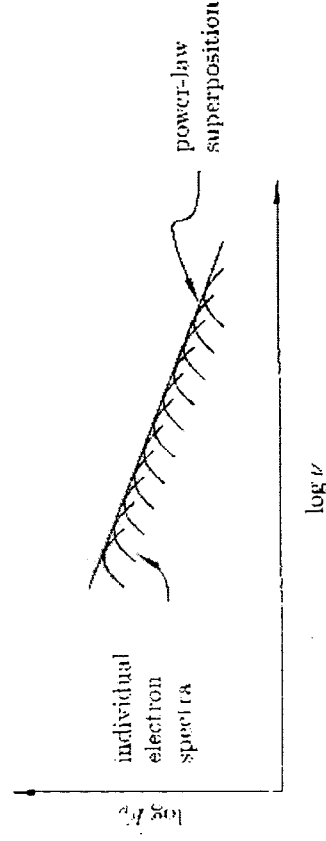
This complex result does lead to one simple conclusion:

$$I(\nu) \propto \nu^{-(\rho-1)/2}$$

or, equivalently  $I(E) \propto E^{-(\rho-1)/2}$

## Synchrotron Radiation

The spectrum from a single electron is **not** a power-law, but if the energy distribution of the electrons is a power distribution, the result appears to be one:



(from Shu, Part II, p 178)

## Synchrotron Radiation

$$N(E) = K E^{-\rho} dE \quad \text{for } E_1 < E < E_2$$

We know  $\rho$ ; can we get  $K$ ,  $E_1$ ,  $E_2$ , or  $B$ ?

Average the previous equations over all directions of magnetic field (for astrophysical applications), where  $L$  is the size of the radiating region:

$$I(\nu) = a(\rho) \frac{e^3}{mc^2} \left(\frac{3e}{4\pi m_e c^5}\right)^{(\rho-1)/2} B^{(\rho+1)/2} K L \nu^{-(\rho-1)/2} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ Hz}^{-1}$$

$$\text{where } a(\rho) = \sqrt{\frac{3 \cdot 2^{(\rho-1)} \Gamma(\frac{3\rho-1}{12}) \Gamma(\frac{3\rho+19}{12}) \Gamma(\frac{\rho+5}{4})}{\pi \cdot 8(\rho+1) \Gamma(\frac{\rho+7}{4})}}$$

## Synchrotron Radiation

Estimating the two boundaries energies  $E_1$  and  $E_2$  of electrons radiating between  $\nu_1$  and  $\nu_2$  can be done using the following results:

$$E_1(\nu) \leq m_e c^2 \sqrt{\frac{4\pi m_e c \nu_1}{3e B y_1(\rho)}} = 250 \sqrt{\frac{\nu_1}{B y_1(\rho)}} \text{ eV}$$

$$E_2(\nu) \leq m_e c^2 \sqrt{\frac{4\pi m_e c \nu_2}{3e B y_2(\rho)}} = 250 \sqrt{\frac{\nu_2}{B y_2(\rho)}} \text{ eV}$$

Tabulations of  $y_1(\rho)$  and  $y_2(\rho)$  are available. Note that if

$\nu_2 / \nu_1 \ll y_1(\rho) / y_2(\rho)$  or if  $\rho < 1.5$  this is only rough estimate

## Synchrotron Radiation

As one might expect, synchrotron radiation can be quite polarized. The total polarization:

$$\frac{P_{\perp}(\omega) - P_{\parallel}(\omega)}{P_{\perp}(\omega) + P_{\parallel}(\omega)} = \frac{\rho + 1}{\rho + 7/3}$$

can be very high (more than 70%).

## Synchrotron Self-absorption

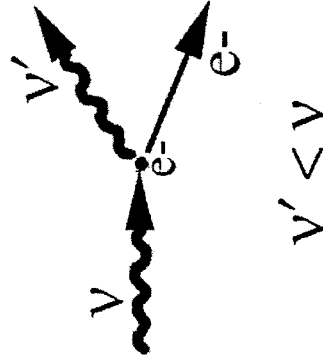
The principal of invariance under time reversal suggests that any emission process can also be an absorption process.

Here, a photon interacts with a charged particle in a magnetic field and is absorbed; the process is stronger at low frequencies/energies. Below the "break frequency"  $\nu_m$ , we have the result that

$$P \propto \frac{\nu^{5/2}}{\sqrt{B}}$$

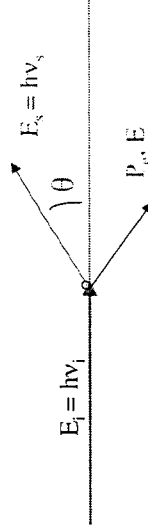
independent of the spectral index.

## Compton Scattering



## Compton Scattering

For low energy photons ( $h\nu \ll mc^2$ ), scattering is classical Thomson scattering ( $E_i = E_s$ ;  $\sigma_T = 8\pi/3 r_0^2$ )



$$\text{where } E_s = \frac{E_i}{1 + \frac{E_i}{m_e c^2} (1 - \cos \theta)} \quad \text{or}$$

$$\lambda_s - \lambda_i = \lambda_c (1 - \cos \theta) \quad \lambda_c \equiv \frac{h}{m_e c} = 0.02426 \text{ \AA}$$

Note that  $E_s$  is always smaller than  $E_i$

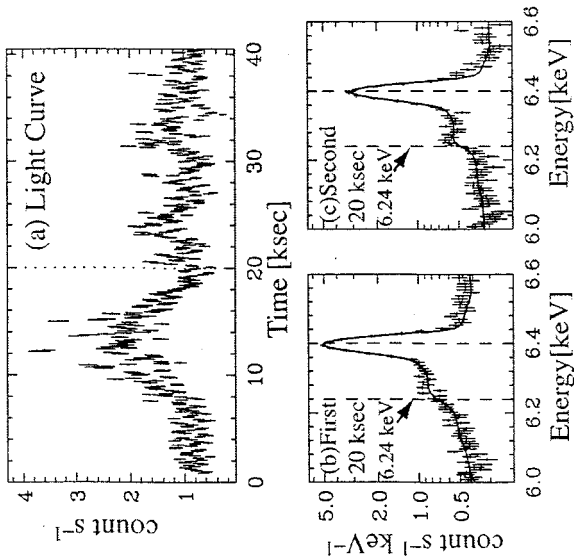
## Compton Scattering

This has been detected using the Chandra HETG and the Fe K 6.4 keV fluorescence line from the XRB GX301-2 (Watanabe et al. 2003)

Here  $E = 6.4$  keV, so  
 $\lambda = 12.398/E = 1.937 \text{ \AA}$

$$\lambda_s - \lambda_i = \lambda_c (1 - \cos \theta)$$

$$\lambda_s = \lambda + 2\lambda_c = 1.986 \text{ \AA} \text{ or } E = 6.24 \text{ keV (if } \Theta = 180^\circ)$$



## Inverse Compton Scattering

If the electron kinetic energy is large enough, energy can be transferred from the electron to the photon:

### Inverse Compton

Use the previous formula (valid in the rest frame of the electron) and then Lorentz transform:

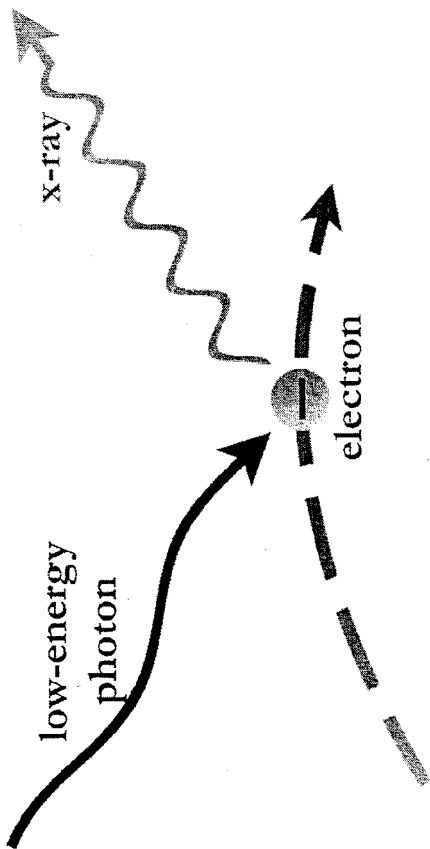
$$E_i^{\text{foe}} = E_i^{\text{lab}} \gamma (1 - \beta \cos \theta)$$

$$E_s^{\text{foe}} = f_{\text{comp}} (E_i^{\text{foe}})$$

$$E_s^{\text{lab}} = E_s^{\text{foe}} \gamma (1 + \beta \cos \theta')$$

which means that  $E_s^{\text{lab}} \propto E_i^{\text{lab}} \gamma^2$  (potentially quite large!)

## Inverse Compton Scattering



## Inverse Compton Scattering

The total power emitted via this process is:

$$P_{\text{comp}} = \frac{4}{3} \sigma_T c \gamma^2 U_{\text{ph}} (1 - f(\gamma, E_i^{\text{lab}}))$$

$$\text{or } P_{\text{comp}} \sim \frac{4}{3} \sigma_T c \gamma^2 \beta^2 U_{\text{ph}}$$

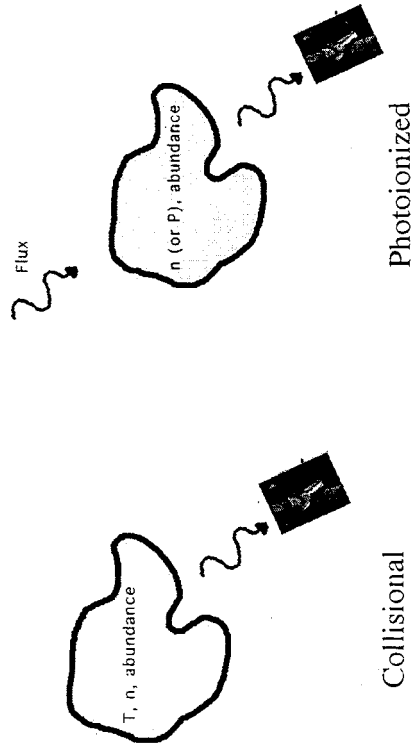
where  $U_{\text{ph}}$  is the initial photon energy density

$$\text{Remember that } P_{\text{sync}} \propto \gamma^2 c \sigma_T U_B$$

$$\text{So: } \frac{P_{\text{sync}}}{P_{\text{comp}}} = \frac{U_B}{U_{\text{ph}}}$$

So synchrotron radiation can be thought of as inverse Compton radiation from the “virtual” photons in the magnetic field.

## Photoionized Plasmas



## Photoionized Plasmas

What happens when an external photon source illuminates the gas?

- The photons ionize the atoms in the gas.
- The photoelectrons created in this way collide with ambient electrons (mostly) and heat the gas
- The gas cools by radiation
- The gas temperature adjusts so that the heating and cooling balance

In a photoionized gas the *temperature* is not a free parameter and

The *ionization balance* is determined by the shape and strength of the *radiation field*

## Photoionized Plasmas

	Photoionized	Coronal
Dominant ionization	Photoionization $h\nu + Z \rightarrow Z+1$	Electron impact $e^- + Z \rightarrow Z+1$
examples	Active galaxies (AGN) binary stars with collapsed companion H II regions	Stellar coronae Supernova remnant Clusters of galaxies
Spectral signature	Absorption, bound-free, bound-bound Emission: recombination	Emission lines, $\Delta n=0, 1, 2$ favored

## Photoionized Plasmas

### Consequences of Photoionization

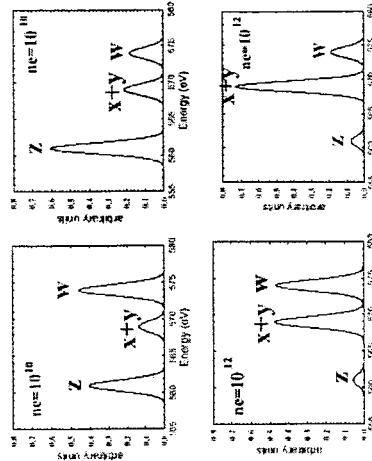
- Temperature lower for same ionization than coronal,  $T \sim 0.1 E_{\text{eff}}/k$
- Temperature is not a free parameter
- Temperature depends on global shape of spectrum
  - At high ionization parameter, the gas is fully ionized, and the temperature is determined by Compton scattering and inverse  $T = \langle E \rangle / 4k$
- Ionization balance is more 'democratic'
- Microphysical processes, such as dielectronic recombination, differ
- Observed spectrum differs

## Photoionized Plasmas

- In coronal gas, need  $kT_e \sim \Delta E$  to collisionally excite lines.
- In a photoionized gas there are fewer lines which satisfy this condition.
- Excitation is often by recombination cascade
- Also get recombination continua (RRCs) due to recombination by cold electrons directly to the ground state. The width of these features is directly proportional to temperature
- Due to the democratic ionization balance, it is more likely that diverse ions such as N VII, O VIII, Si XIV can coexist and emit efficiently than it would be in a coronal gas
- Inner shell ionization and fluorescence is also important in gases where the ionization state is low enough to allow ions with filled shells to exist.

## Photoionized Plasmas

### Density dependence of He-like lines



### Coronal photoionized

(Porquet and Dubau 1998)

## Photoionized Plasmas

Parameter definitions:

$$\xi \equiv \frac{L}{n_e R^2} \quad \text{Tarter, Tucker \& Salpeter (1969)}$$

$$U_r \equiv \frac{N_X}{4\pi R^2 n_c} \quad \text{Davidson (1974)}$$

$$\Gamma \equiv \frac{L_X(> 13.6 \text{ eV})}{8\pi R^2 n_c} \quad \text{Kwan \& Krolik (1981)}$$

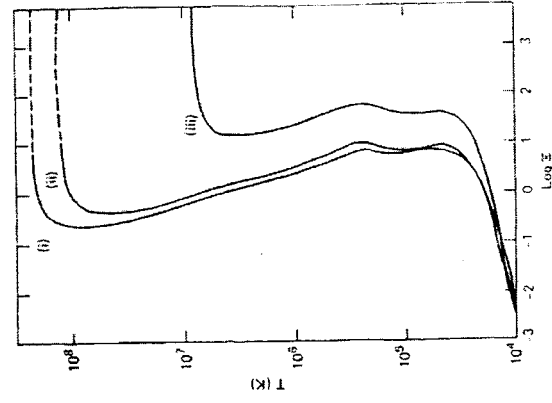
$$\bar{\Xi} \equiv \frac{L}{4\pi n_e c k T R^2} \quad \text{Krolik, McKee \& Tarter (1982)}$$

$$U_I \equiv \frac{N}{4\pi R^2 n_c} \quad \text{Netzer (1994)}$$

where:

$$L \equiv \int_{13.6 \text{ eV}}^{\infty} L(E) dE \quad N \equiv \int_{13.6 \text{ eV}}^{\infty} L(E) \frac{dE}{E} \quad N_X \equiv \int_{100 \text{ eV}}^{\infty} L(E) \frac{dE}{E}$$

## Photoionized Plasmas



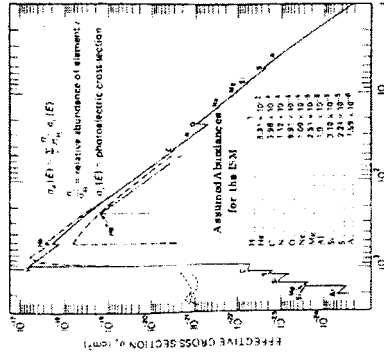
### 'Thermal Instability'

- For gas at constant pressure, thermal equilibrium can be multiple-valued if the net cooling rate varies more slowly than  $\Lambda(T) \sim T$
- This suggests the possibility of 2 or more phases coexisting in pressure equilibrium
- The details depend on atomic cooling, abundances, shape of ionizing spectrum.

Krolik, McKee and Tarter 1981

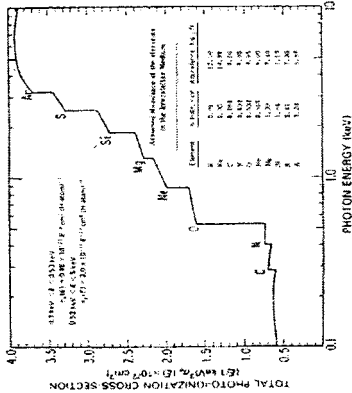
# Absorption

- Absorption by interstellar material is in every spectrum, but absorption is uniquely associated with photoionized sources.
- A crude approximation for the photoabsorption cross section of a hydrogenic ion is that the cross section is  $\sim Z^{-2}$  at the threshold energy, and that the threshold energy scales  $\sim Z^2$ .
- In addition, the cosmic abundances of the elements decrease approximately  $\sim Z^{-4}$  above carbon
- So the net cross section scales as  $E^{-3}$ , and large jumps in absorption are not expected at the thresholds.
- Detection of such edges are indicative of abundance anomalies or partial ionization of the gas



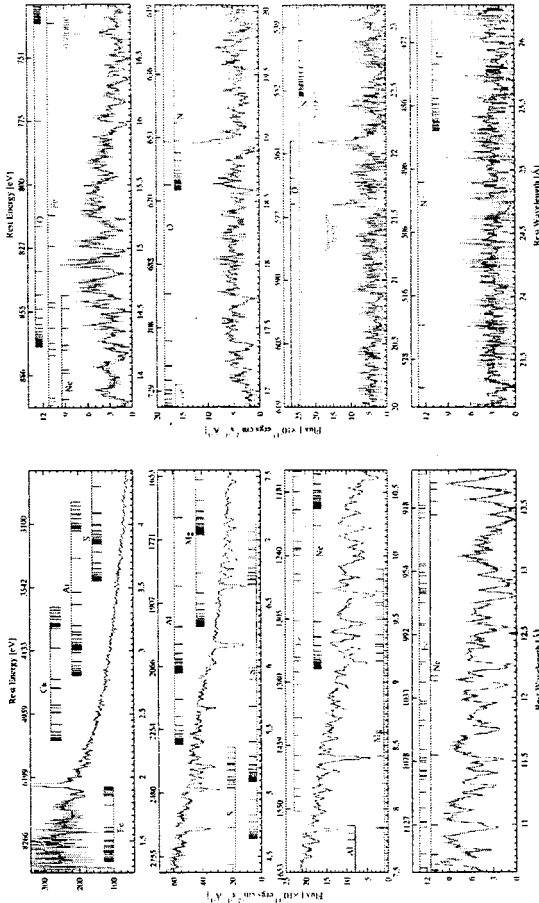
Interstellar absorption (Morrison and McCammon; Zombeck)

# Absorption



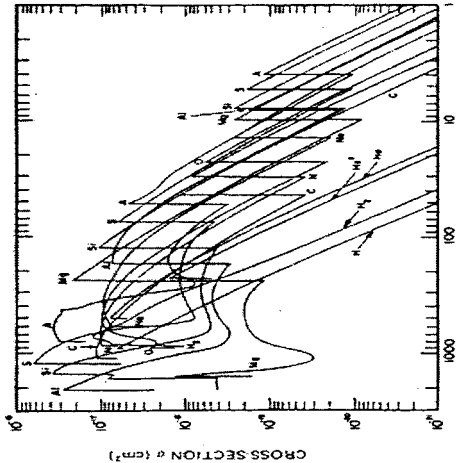
NGC 3783 900 ksec Chandra observation

# Absorption



135 absorption lines identified

# Absorption



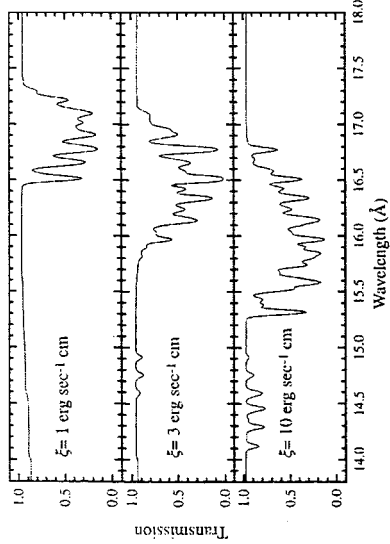
Cross section for photoionization for abundant elements vs. wavelength (Zombeck)



## Unresolved Transition Arrays (UTAs)

## Absorption

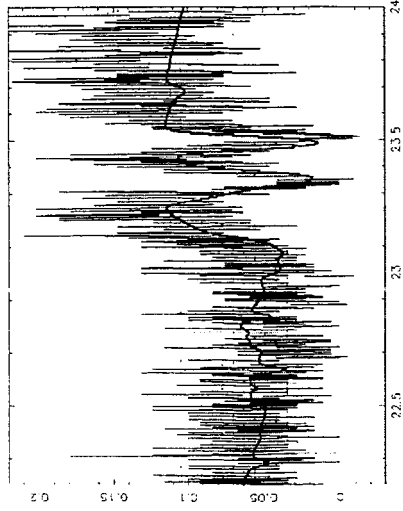
- Appears in absorption spectra of AGN, eg. NGC 3783
- Comes from 2p-3s or 2p-3d transitions --> requires iron less than 9 times ionized
- Potential diagnostic of ionization balance



(Behar, Sako and Kahn 2002)

## Absorption

Spectrum of Cyg X-2 fit with O K edge data

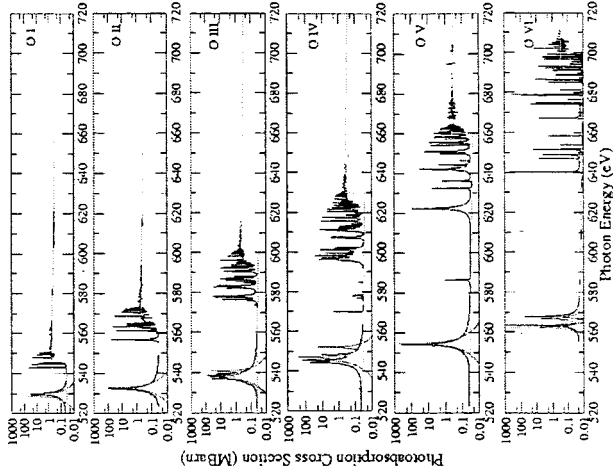


Experimental wavelengths can be used to optimize calculated absorption cross sections, and thereby improve accuracy of more transitions than just those for which measurements exist

## K shell Photoabsorption (Oxygen)

## Absorption

In theory, could diagnose ionization balance in the ISM or other absorbing material. This data uses semi-empirical corrections to energy levels in the optimization of wavefunctions, based on the experiment, plus multi-code approach



Red: Pradhan et al (2003)

Black: Garcia et al. (2005)

## Conclusions

Although moderately complex, there are relatively few processes that dominate X-ray emission; analyzing the observed spectrum from each can reveal the underlying parameters. These processes are:

- Line emission
- Collisional  $\Rightarrow$  temperature, abundance, density
- Photoionized  $\Rightarrow$  photoionization parameter, abundance, density
- Synchrotron emission  $\Rightarrow$  relativistic electrons, magnetic field
- Inverse Compton scattering  $\Rightarrow$  relativistic electrons
- Blackbody  $\Rightarrow$  temperature, size of emitting region / distance<sup>2</sup>
- Absorption  $\Rightarrow$  abundance, density, velocity

## Books and references

- Rybicki & Lightman "Radiative processes in Astrophysics"
- Longair "High Energy Astrophysics"
- Shu "Physics of Astrophysics"
- Tucker "Radiation processes in Astrophysics"
- Jackson "Classical Electrodynamics"
- Pacholczyk "Radio Astrophysics"
- Ginzburg & Syrovatskii "Cosmic Magnetobremmstrahlung" 1965  
Ann. Rev. Astr. Ap. 3, 297
- Ginzburg & Tsytovitch "Transition radiation"